SURFACE TEMPERATURES DUE TO TRANSIENT HEAT FLOW

CHARLES EARL ARNOLD

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C. E. Arnold

SURFACE TEMPERATURES DUE TO TRANSIENT HEAT FLOW

by

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Submitted in partial fulfillment
of the requirements
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PREFACE

The purpose of this investigation was the determination of the temperature-time history of a metal surface suddenly exposed to high pressure steam.

In the literature dealing with the phenomenon of thermal shock, in order to obtain calculated results, authors have had to assume either; (1) the temperature rise at the surface of the metal was a stepwise function or, (2) the heat transfer coefficient remained constant and the surface temperature was then calculated.

To the best of the authors knowledge, all experimental attempts to determine surface temperature as a function of time due to the sudden admission of high pressure steam into piping systems have been performed using static measuring devices. In one report (1) of such an attempt the first recorded point was five seconds after the admission of the steam.

It was the authors' desire to measure the temperature-time history of the surface of a metal plate exposed to high pressure steam using automatic continuous recording devices, with particular attention being paid to approximately the first five seconds after the first contact between steam and metal surfaces.

The author wishes to express his appreciation for the willing assistance and guidance given him by the Mechanical Engineering Department of the U. S. Naval Postgraduate School. Special acknowledgement is due Professor E. E. Drucker whose continued guidance and advice were invaluable. Special acknowlegement is also due the Army Ordnance Department for supplying the thermocouple probes.

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CHAPTER I

INTRODUCTION

In the literature on thermal shock, a temperature-time history is usually assumed in order to effect calculations - the accuracy of the results depending on the accuracy of the assumed history.

Various attempts have been made to experimentally determine this temperature-time history. Knox (1) published such a study in which the first reading was taken five seconds after the admission of the heating medium. Knox's calculations, and those of Teepe (2), indicate that the most severe thermal stresses occur within the first five seconds after admission of the heating medium.

Bendersky (3) described the development of a new type thermocouple probe for measuring temperatures within one micron (.000039 inches) of a surface.

Two of these thermocouples were obtained through the courtesy of the Army Ordnance Department, with their calibration data. These two thermocouples were used in conjunction with two D. C. pre-amplifiers and a Dumont dual-beam oscilloscope to record the surface temperature of a plate of SAE 4130 steel suddenly exposed to steam (90 to 140 psia).

CHAPTER II

EQUIPMENT

Figure 1 is a schematic diagram of the complete test arrangement showing steam and electrical circuits.

The test arrangement falls naturally into three groups:

1. The steam path and test section.
2. Measuring instruments.
3. Recording instruments.

1. Steam path and test sections:

(a) Figure 2 shows the arrangement of the piping used. All piping was 2" standard steel piping assembled using threaded fittings.

(b) Thermocouples (See figure 5).

The major parts of the thermocouples are the probe, body, terminal posts and insulator. The most important of these is the probe, which contains the junction. The probe consists of a thick walled steel tube plated on one end with a thin layer (1 micron, i.e. 3.9×10^{-5} inches of nickel). The interface between the nickel plating and the end of the probe is the plane at which the thermal emf is generated. The lead wire to the plating is mounted in the center of the tubing. This wire is also made of nickel, and is coated with an oxide of nickel which serves as electrical insulation between the nickel wire and the steel tubing.

The probe ends in a flat plane on which the nickel is deposited.

The probe is held in a steel body. The body is equipped with external threads which are used to mount the unit and also contains the binding post for attaching the external steel lead wire. A lucite insulator is employed between the steel body and the nickel terminal post.*

*Bendersky - A THERMOCOUPLE FOR MEASURING TRANSIENT TEMPERATURES - Paper Number 52-A-57 - ASME

The flat end of the probes necessitated mounting them in a plate rather than a section of pipe. The probe and body are of SAE 4130 steel, the plate carrying them was fabricated from same steel in order to minimize thermal disturbance due to different thermal properties of probe and test section.

(c) The Test Section

The test section was machined from an SAE 4130 steel forging obtained from the U. S. Naval Gun Factory, Washington, D. C. The surface of the test section was carefully machined to approach the fine finish of the nickel plating of the thermocouple probes. The test section was so prepared that when installed, its exposed face would be flush with the inner surface of the test section carrier.

The steam seal is provided by a taper fit backed by a composition gasket and "Aviation Permatex No. 2". The assembled unit was hydrostatically tested to 450 psig without leakage.

The thermocouples were mounted in carefully prepared holes which give a firm interference fit along the probe barrel, and are adjusted flush with the face of the test section. Lock nuts maintain this careful alignment.

The steam seal around the thermocouples is provided by the interference fit and plastic washers crushed between the body of the thermocouples and the test section.

Four beaded copper-constantan thermocouples are provided in addition, buried in the test section at two different depths (0.21" and 0.42" from the exposed face as shown in figure 3c.).

All thermocouples are mounted evenly spaced on a line perpendicular to the direction of steam flow.

(d) The test section carrier (figure 3a)

The test section carrier was designed to provide a relatively smooth transition from the round cross section of the auxiliary piping to the rectangular cross section necessitated by the test section and to maintain the cross sectional area relatively constant. A steam run of about two feet is provided by the carrier to allow the steam flow to stabilize.

The test section carrier is made up of half inch mild steel plates welded together as shown in figure 3a.

Thermal isolation of the test section was accomplished by the use of insulating gaskets between the flanges joining the test section carrier to the auxiliary piping and by lagging the by pass piping to minimize radiation to the test section. The test section and carrier are not lagged to provide for faster cooling between runs.

(e) Auxiliary piping (figure 2.).

The auxiliary piping was arranged so that the thermodynamic state of the steam could be established and the mass rate determined before being admitted to the test section.

The inlet throttling valve was provided to reduce steam pressure from line pressure to that desired for the run. The exhaust throttling valve was provided to control the mass rate.

2. Measuring Instruments

The measuring instruments consist of pressure gage, thermometers,

throttling calorimeter, weigh tank and scale balance. A heater was provided to dry the steam.

A by pass pipe was provided around the test section to carry the steam before a run was made. The test section carrier was protected from the steam by a quick opening valve at the inlet end and a check valve at the exhaust end. The by pass piping was similarly equipped to assure that all steam passed through the test section after a run was commenced.

The details of the electrical circuits provided are shown in figure 4.

3. Data recording instruments (figure 1.)

From the calibration curves supplied with the surface thermocouples, it was determined that the maximum signal strength to be expected would be about 5 millivolts under open circuit conditions. In order to make dynamic measurements of the thermocouple output, it was necessary to employ an oscilloscope and a preamplifier. The very high input impedance to the preamplifier allowed the thermocouples to operate under essentially open circuit conditions.

The components used were:

One Dumont Dual-Beam Cathode Ray Oscillograph Type 322

The x, and y axes were rotated 90° by means of connections provided.

Two Brush Developement Company D. C. Amplifiers Model BC 932 (1 each channel)

One Fairchild Oscillo-Record Camera and Motor Controller unit Model F-246A. Uses 35 mm film (LOC 520 Kodak linograph ortho).

A calibrating voltage source was constructed using a one and a half volt dry cell, a 200,000 ohms rheostat and a calibrated 1000 ohms Heliopot potentiometer. The voltage drop across the Heliopot was adjusted to ten millivolts. This allowed a very accurate control of the calibrating voltages (one millivolt $\pm$ 1%).

Only two thermocouples could be used in any given run. The author used the surface thermocouples for most runs, and thermocouple #4 for one run each, at 90 psia and 140 psia.

All external leads were shielded and grounded to minimize stray pick up.

CHAPTER III

PROCEDURE

Before each run, the amplifiers and the oscilloscope were allowed to warm up for at least 40 minutes. Steam was admitted to the auxiliary piping and allowed to thoroughly heat the piping to remove as much condensation as possible.

The pressure was adjusted to that desired for the run and by use of the heater, the steam was dried until the throttling calorimeter indicated no moisture.

Using the Fairchild camera on single frame exposure, 2.5 and 5 millivolts were applied to the amplifier-oscilloscope system and recorded (1/50 second at f1.9 using vertical sweep frequency of 60 cps). The thermocouples were then plugged into the amplifier and the motor drive set for 6 inches per second. A timing trace is provided in the camera, it is energized by a 60 cycle A.C. 115 V source giving 120 "pips" per second.

The quick opening valves were manipulated to switch the steam to the test section. After about 20 seconds, the run was stopped.

The pressure, temperature and mass rate were measured before and after each run.

CHAPTER IV

RESULTS

The results are presented as combined plots of surface temperature difference, versus time.

Figure 9 presents the results of the average of four runs using 90 psia saturated steam.

Figure 10 presents the results of the average of four runs using 140 psia saturated steam.

Figure 11 presents the combined average of all eight runs.

When the individual runs are plotted separately, they show considerable dispersion, much more than the uncertainty (about 15°) in determining the instantaneous temperatures. This large dispersion is due to several factors:

1. Inability to determine precisely the moment the steam arrived at the thermocouples.

2. Surging flow during the first second or so of the run. When the quick opening valves were manipulated to switch the flow through the test section a pressure pulse coursed through test section carrier, hit the check valve and was reflected back down the chamber, the check valve reseated. This process was repeated three or four times before the check valve remained open. These pressure pulses, rarefactions and compressions, have an undetermined effect on the rate of heat transfer to the metal surface.

3. Any condensation on the face of the probes would have an insulating effect until carried away by the steam flow.

4. Uncertainties in determining the true displacement of the film trace due to:

(a) Amplifier "noise" and stray pick up.

Attempts to increase the displacement by increasing the gain of the preamplifier or the oscilloscope resulted in greatly increased "noise".

(b) Limited accuracy in measurements.

A Simmons Omega D2 enlarger was used to project the 35 mm film of the run on to graph paper where the measurements were made (to the nearest .01 inches) using dividers and an engineer's scale.

Averaging the runs lessened this random dispersion and the points more closely approached a smooth curve.

The variation in mass rate had no apparent effect on the rate of surface temperature rise.

The 33°F difference between the two sets of runs had no apparent effect, in the duration of the run, on the rate of surface temperature rise. At least, the effect was less than the uncertainty in determining the instantaneous temperatures.

In view of the above, all eight runs were averaged and plotted.

Figure 12 shows the eight run average plotted on a log-log plot of temperature difference versus time with constant coefficient of heat transfer ("H" - $^{BTU}/hr - ft^2 - {}^{\circ}F$) lines shown (2). From this plot, it can be seen qualitatively that "H" rises from about 975 at 0.1 seconds to about 1075 at 0.2 seconds and then decreases to about 700 at 1 second.

Figure 13 is an enlargement of a portion of run #3.

Figure 14 is an enlargement showing the response of the data recording system to a step input of 5 millivolts.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

The instrumentation used is inherently capable of producing accurate results.

To a large extent, the variations between runs were real variations due to surging flow and condensation on the face of the thermocouple probes.

The assumption of a constant coefficient of heat transfer when calculating surface temperatures as a boundary condition in heat transfer problem is a valid one, at least for the first 5 or so seconds.

Once enough runs have been made to establish the true mean curve of the rate surface temperature rise, this type instrumentation can be used to measure variations from this mean in particular cases.

Further experimentation is in order.

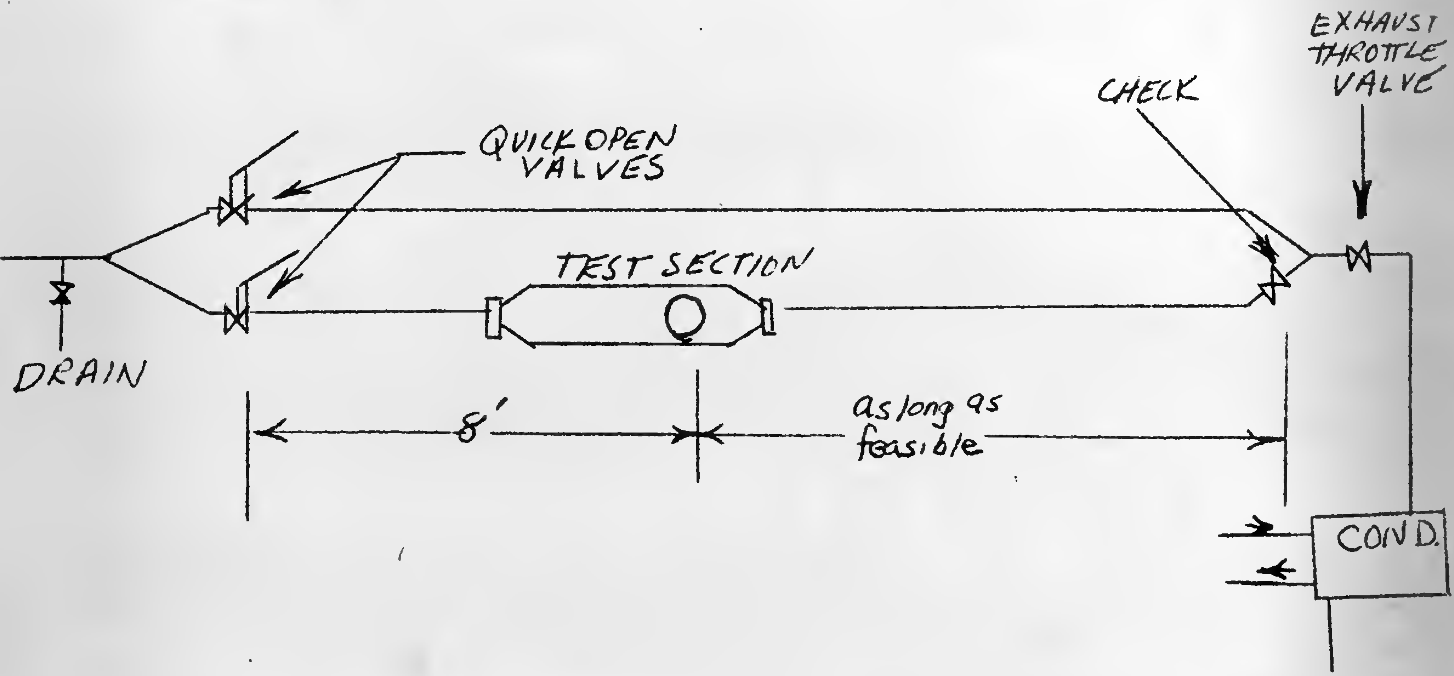
Recommendations:

Less "noisy" preamplifiers should be procured, and strenuous efforts should be made to further decrease stray pick up.

The effect of superheated and moist steam should be investigated.

Higher pressures should be used - up to 400 pounds with the test section as installed.

A possible means of eliminating the surging flow would be to provide a longer steam run (about 8 feet) before the steam reaches the test section, and to place the check valve as close to the exhaust throttling valve as possible.



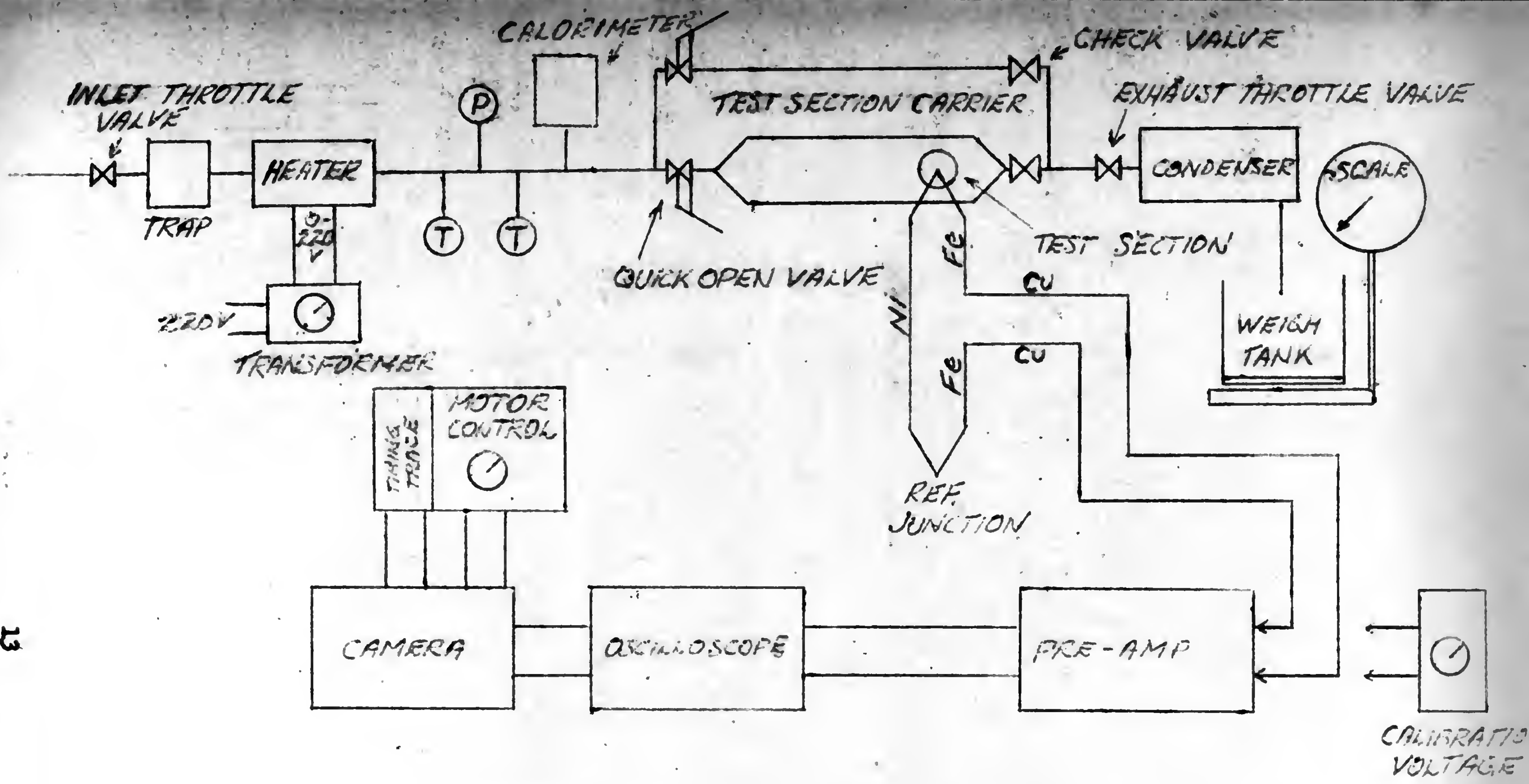


FIG. 1 COMPLETE TEST SETUP

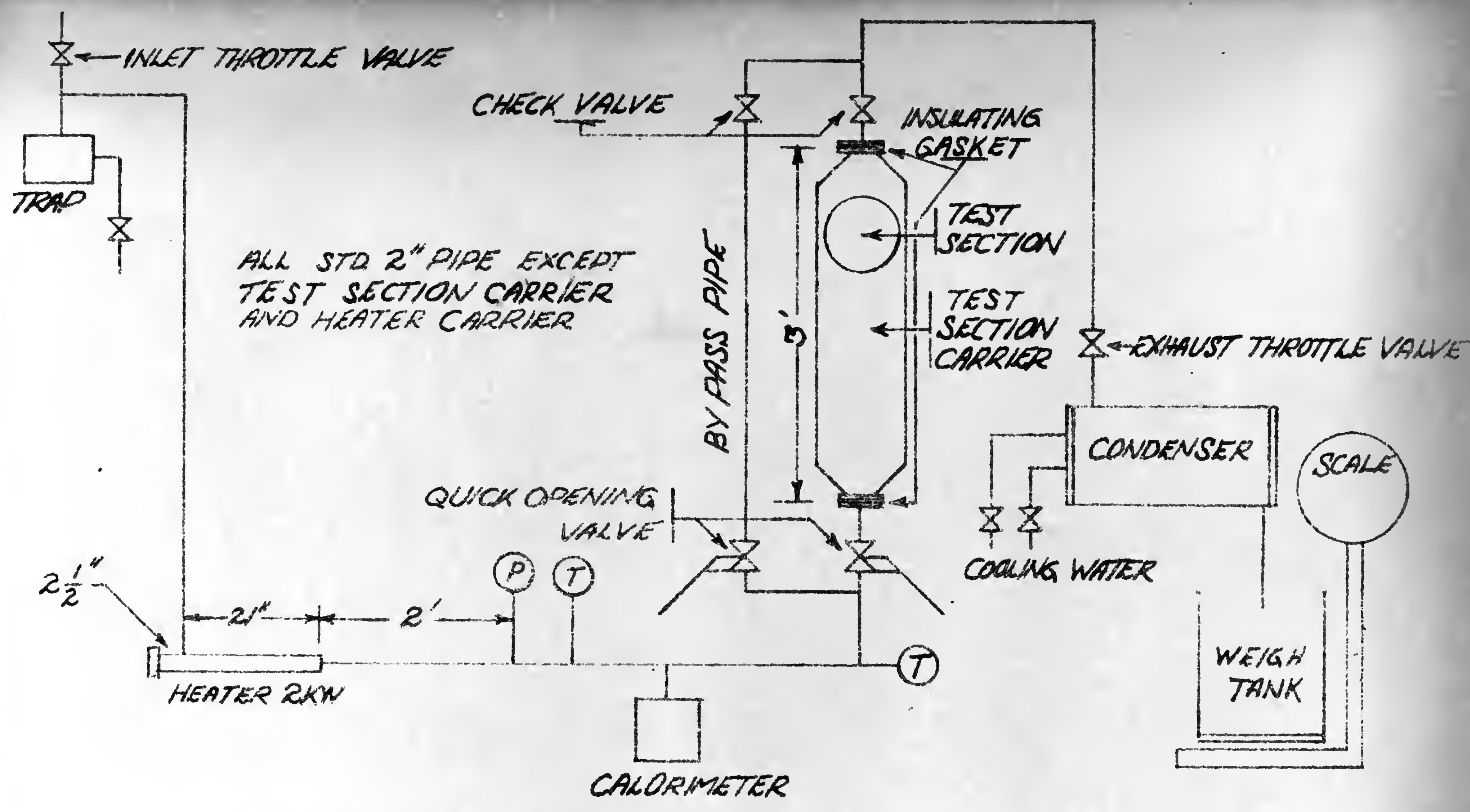


FIG. 2 DETAILED PIPING ARRANGEMENT

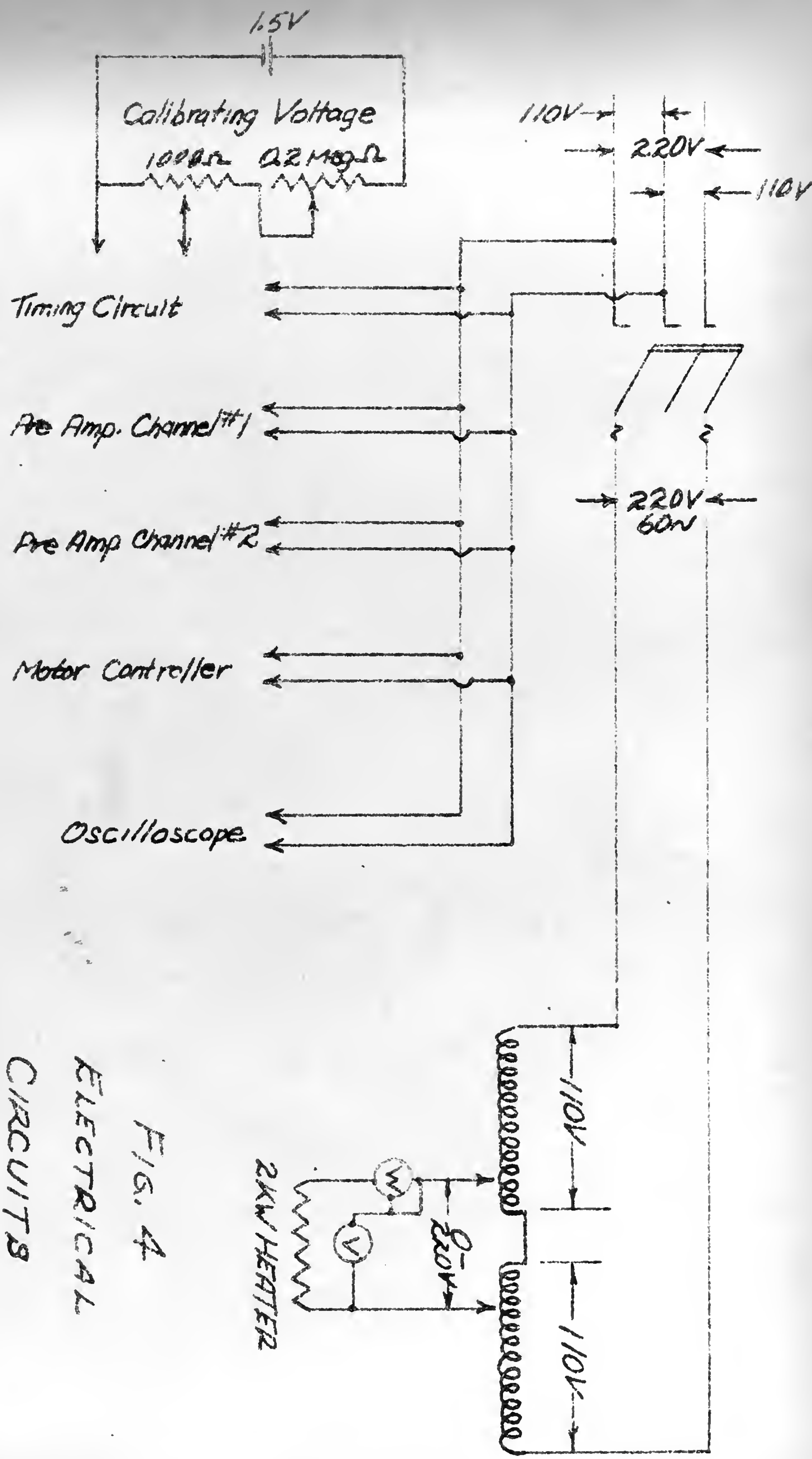


FIG. 4
ELECTRICAL
CIRCUITS

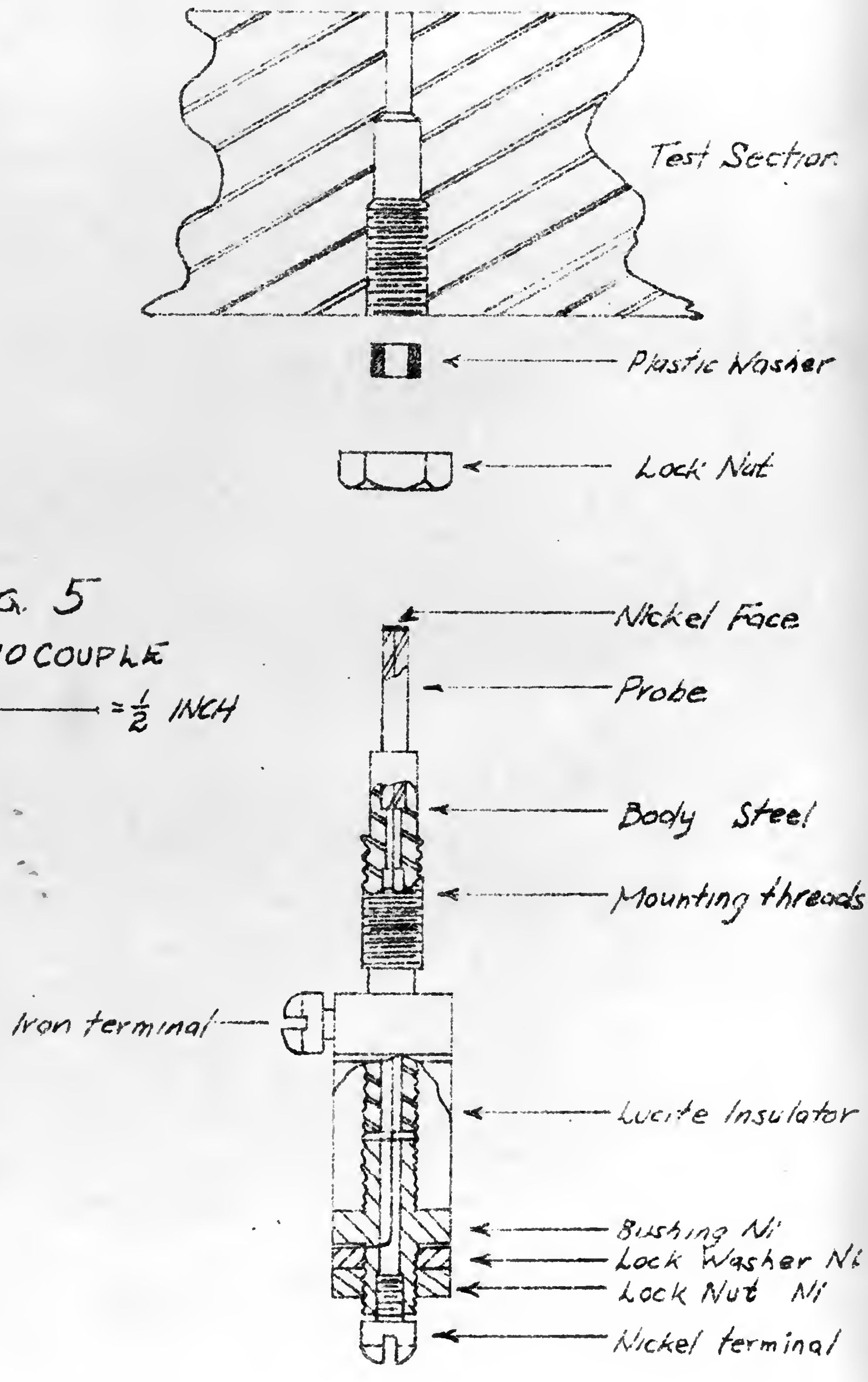
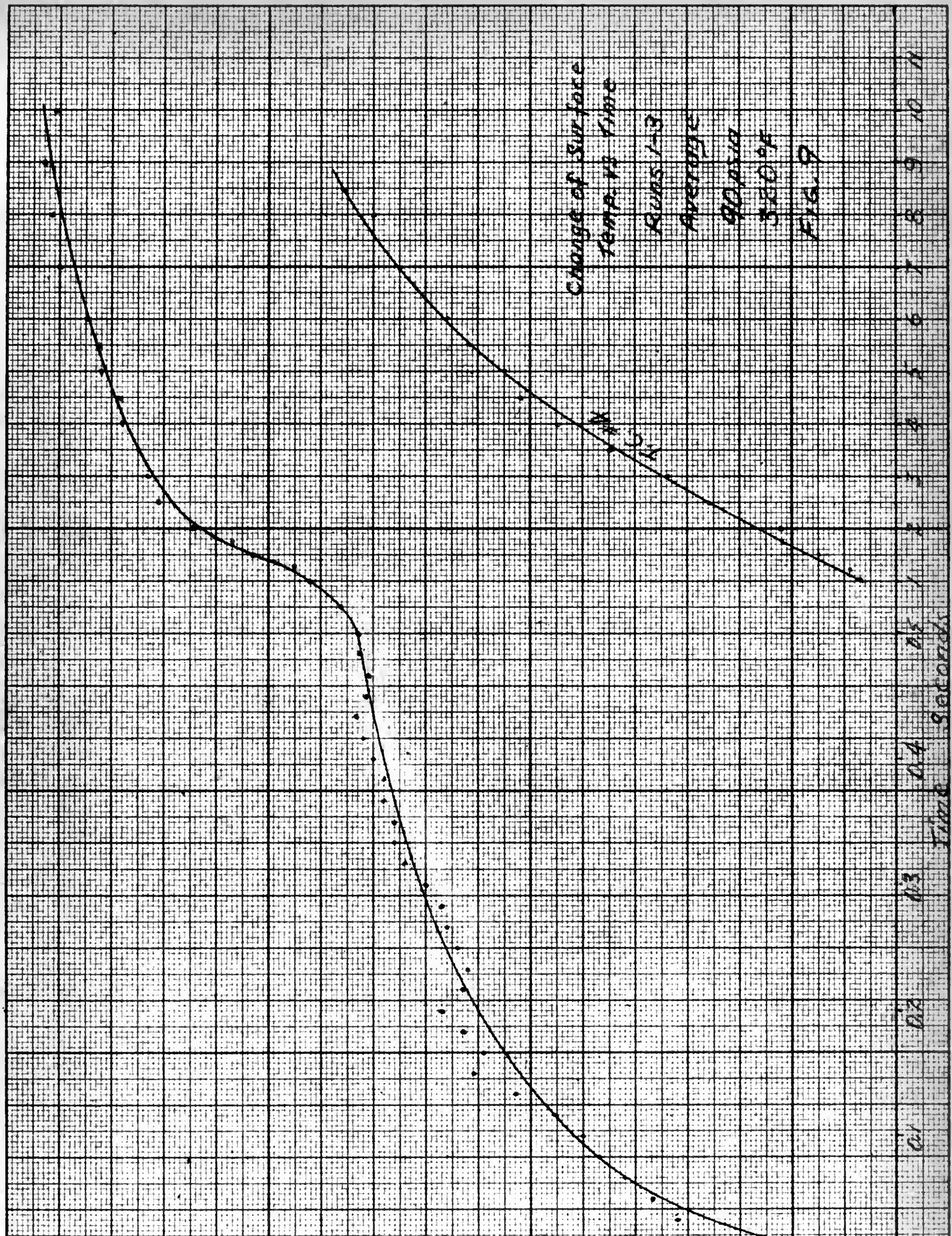
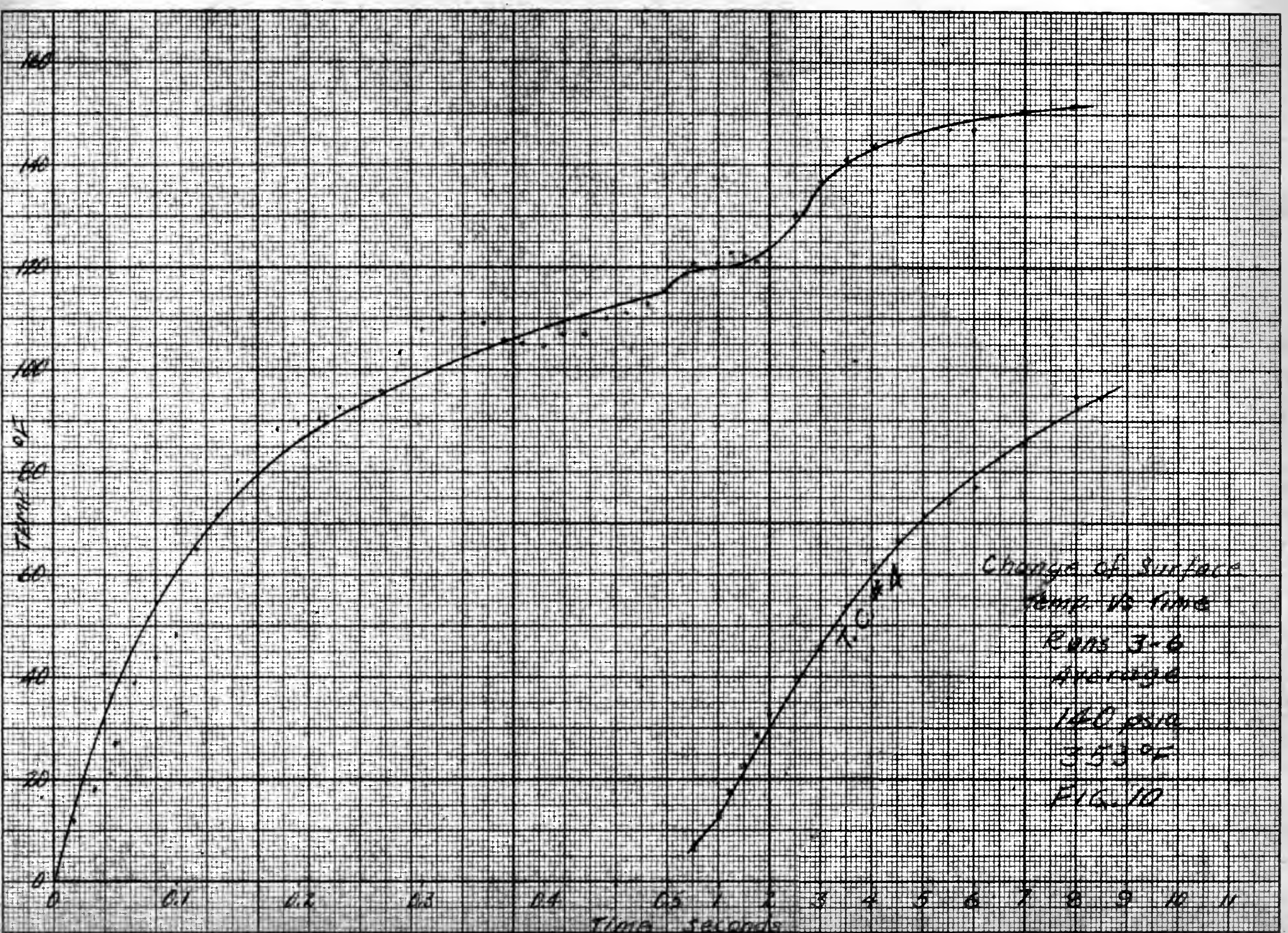
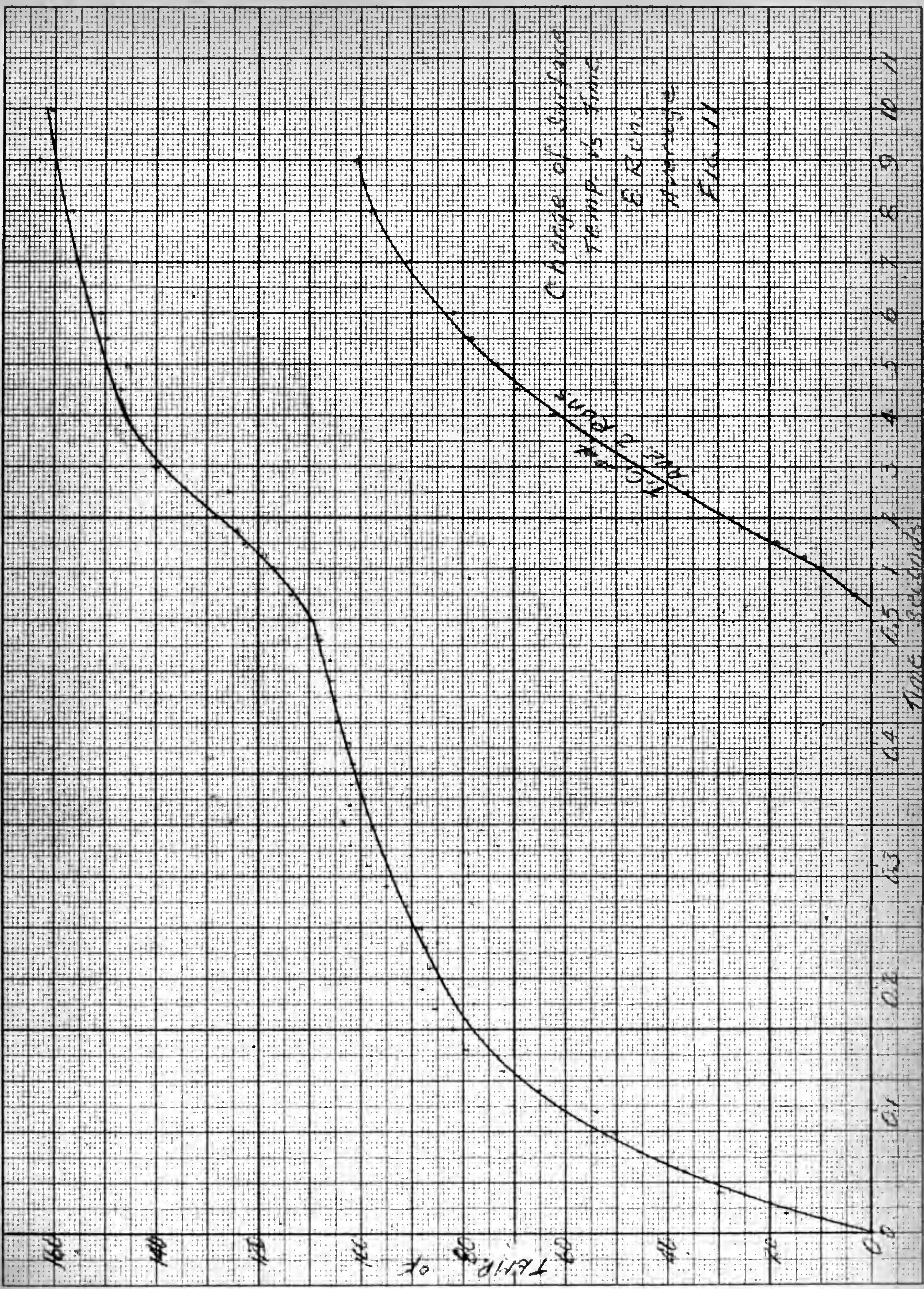
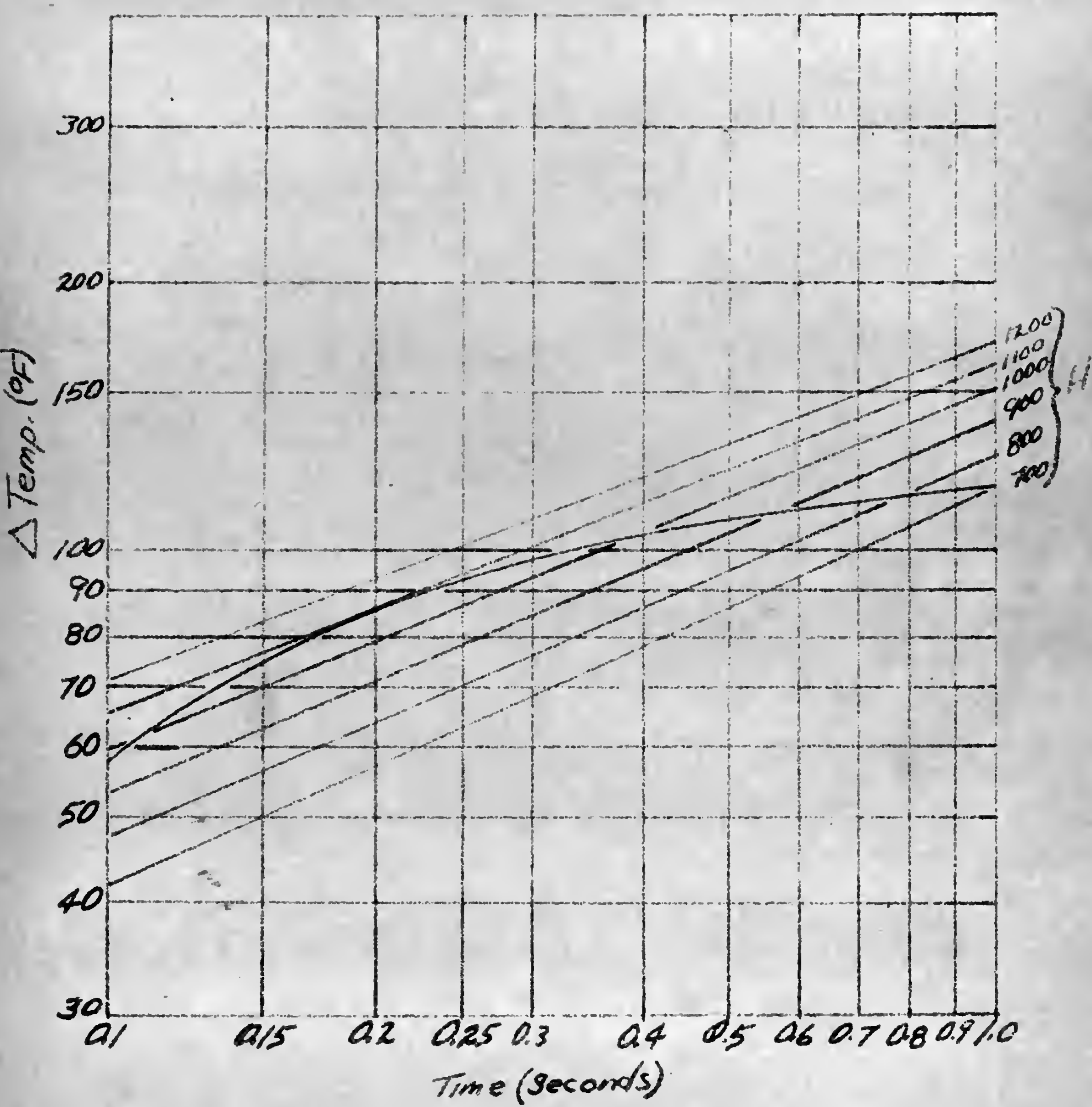


FIG. 5
THERMOCOUPLE
SCALE ——— = $\frac{1}{2}$ INCH


Change of Surface
Temp. vs Time
Runs 1-3
Average
90 psia
370°F
Fig. 9
Time Seconds
TEMP °F
0
20
40
60
100
120
140
160
0.1
0.2
0.3
0.4
0.5
1
2
3
4
5
6
7
8
9
10
11


Temp. °F
Time seconds
0
0.1
0.2
0.3
0.4
0.5
1
2
3
4
5
6
7
8
9
10
11
20
40
60
80
100
120
140
160
T.C. #1
Change of Surface
Temp. vs time
Runs 3-6
Average
140 psia
353 °F
FIG. 10


Change of Surface
Temp vs Time
Average
Time seconds
Temp °K



Change Surface Temperature vs Time

FIG. 12

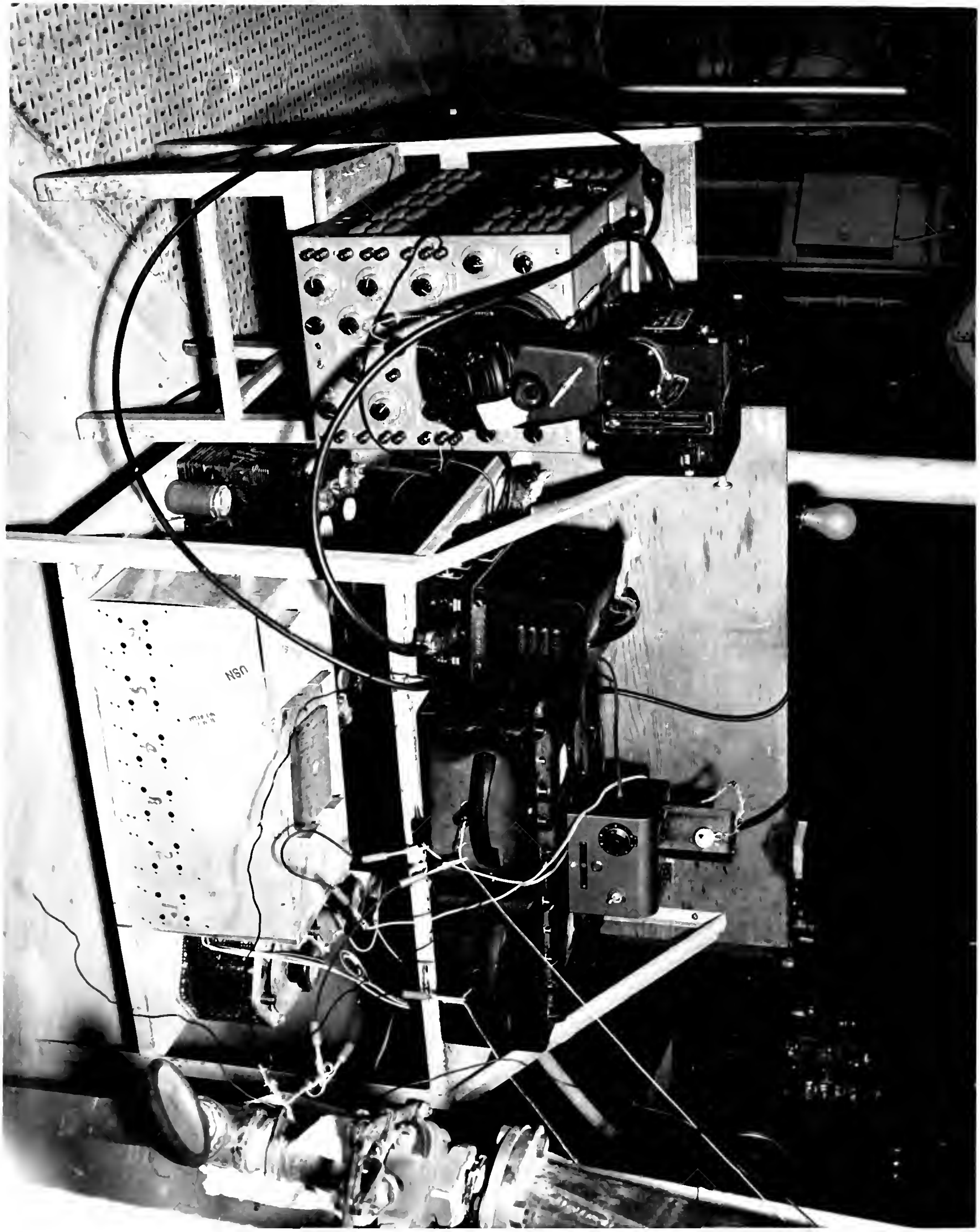


FIG. 6
Pg. 21

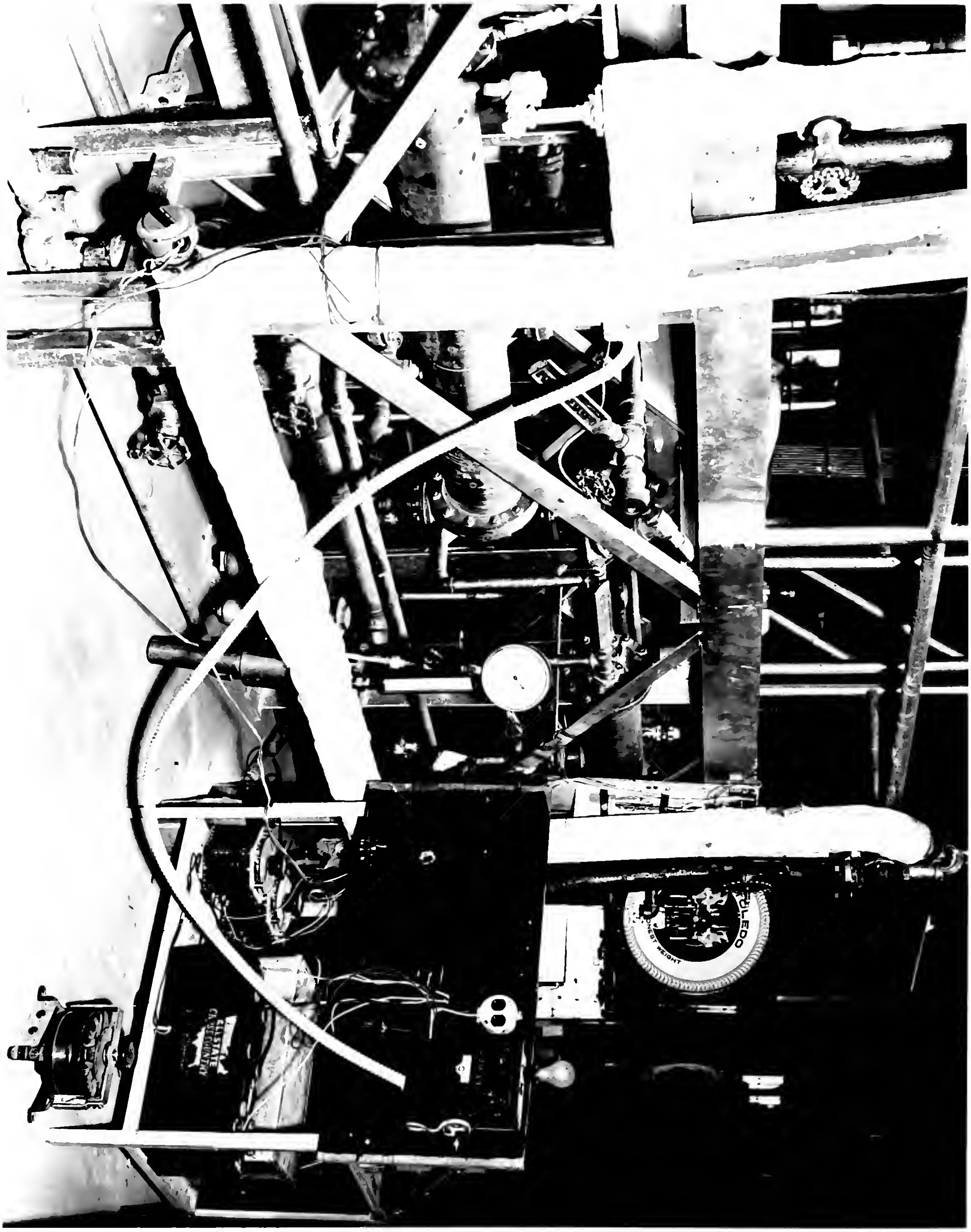


FiG. 7
Pg. 22

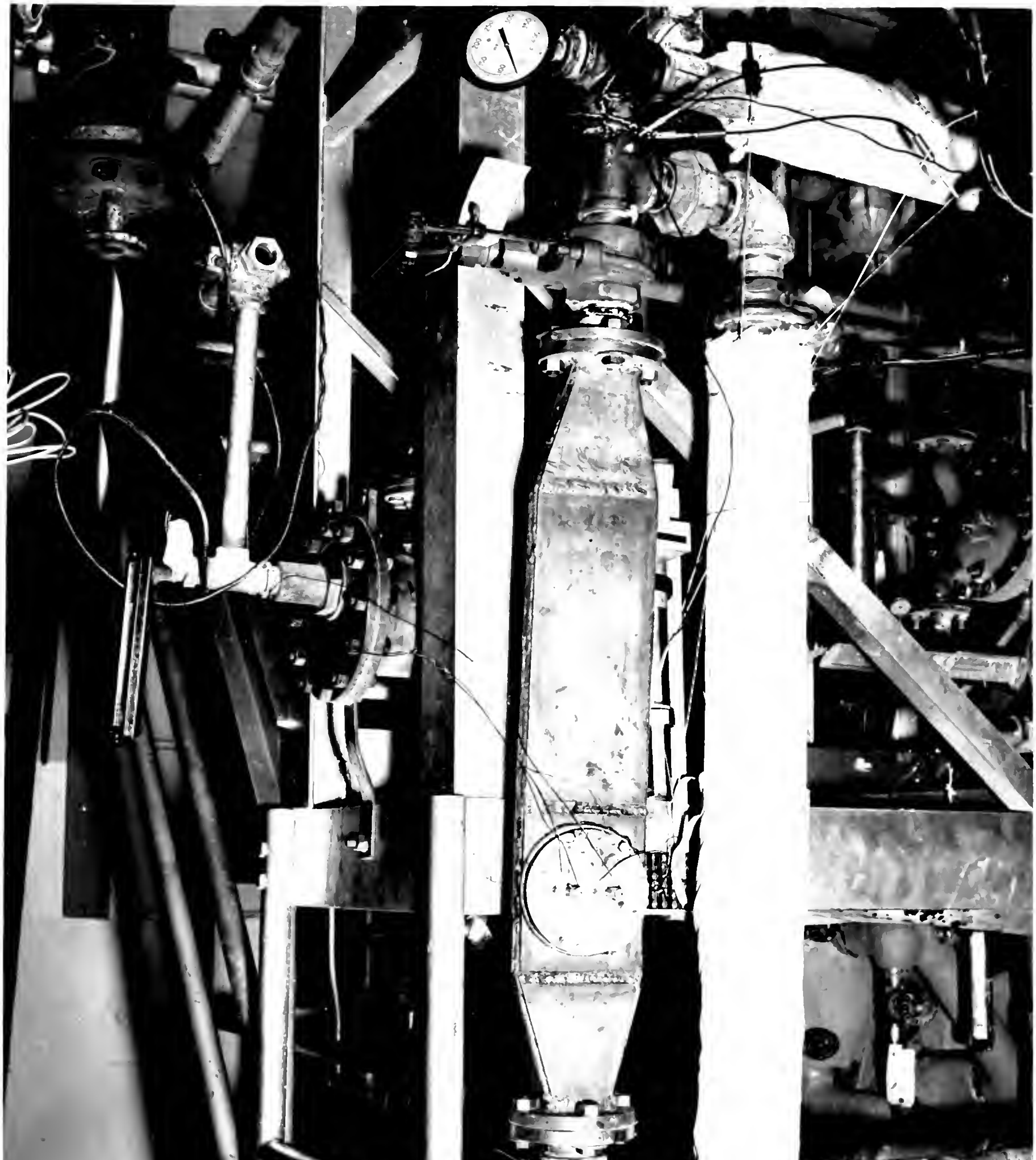
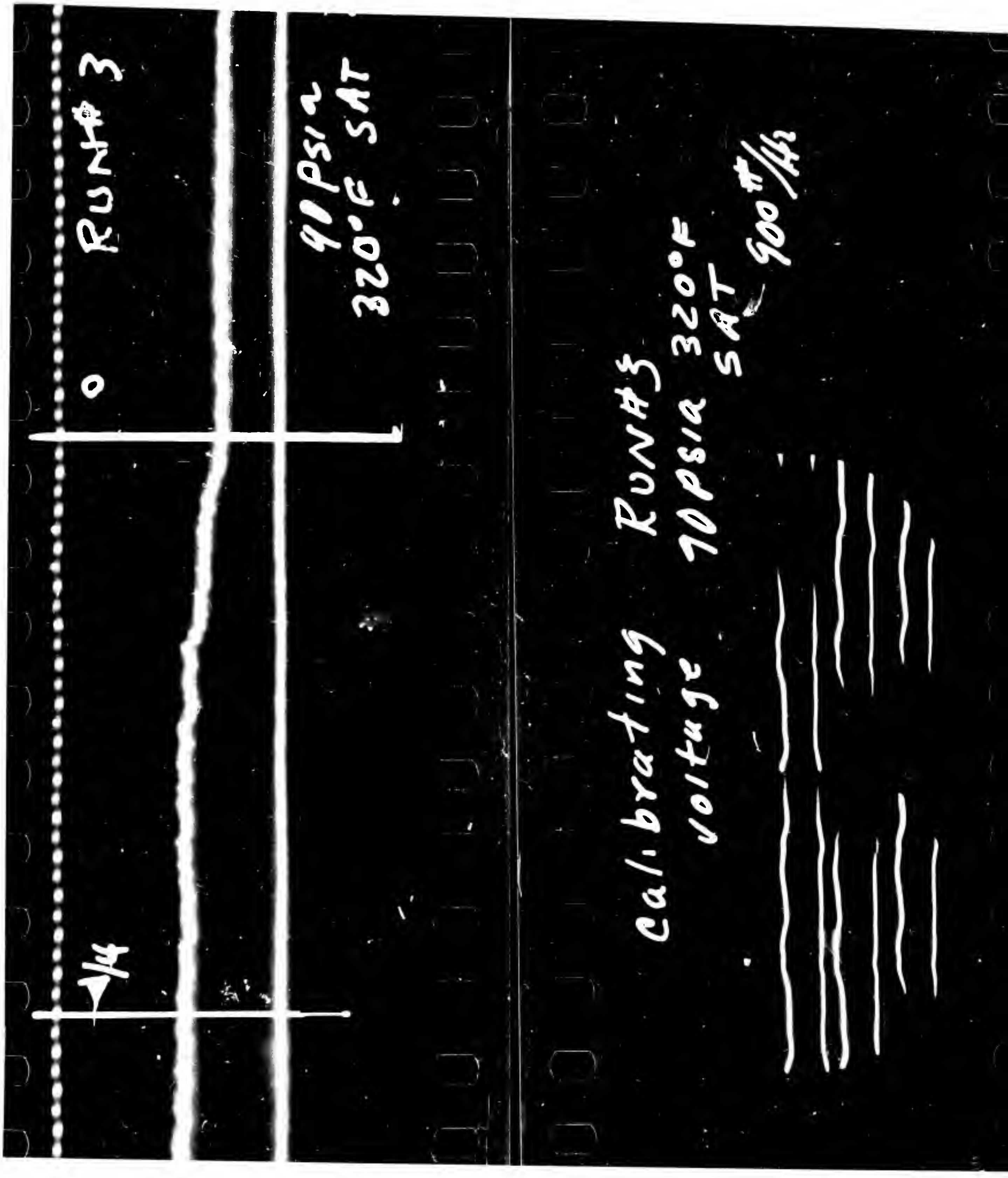
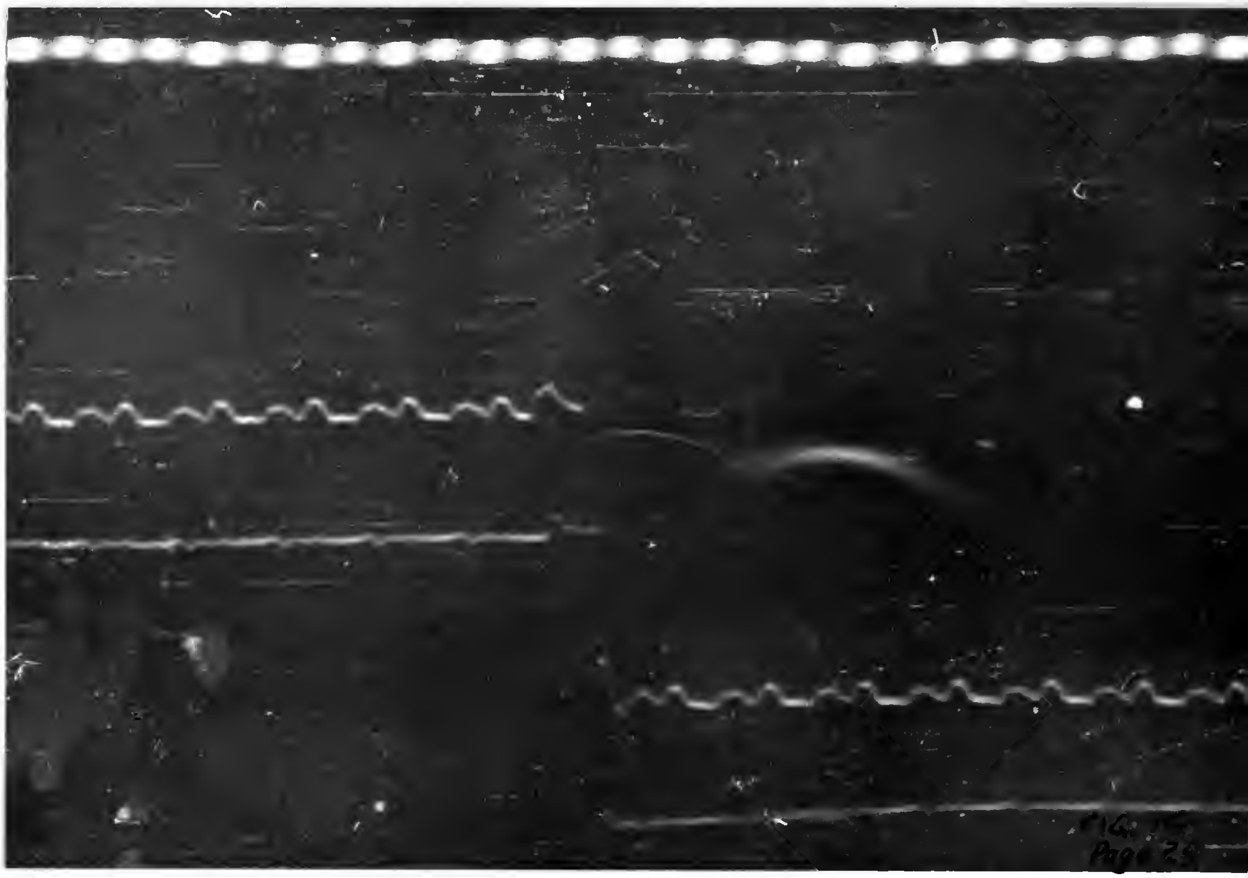


FIG. 8
Pg. 23


RUN# 3
90 PSIA
320°F SAT
calibrating voltage
RUN#3
90 PSIA 320°F
SAT



The method used to reduce the data is illustrated below.

From the projected film, displacements from the edge of the film were measured to the nearest .01".

The displacement of the calibrating voltages was measured to the nearest .01".

The change of surface temperature was determined by the following procedure:

$$\Delta M.V._i = \left[Y_o - Y_i\right] \times \frac{2.5\,(M.V.)}{\Delta Y_c\,(\text{INCHES})}$$

M. V. --Millivolts
Yo -----displacement of base line
Yi -----displacement of film trace
ΔY_c --distance between calibrating traces

Enter the plot of M.V. versus Temp. for the particular thermocouple and pick off the temperature change.

For the range of temperatures involved, the variation of emf with temperature was essentially a straight line.

For the range of signal input to the data recording system, the response was linear.

Data. runs 1-3 90 psia. 320°F saturated steam

Column 1 Time seconds

Column 2 Run #1 T.C. #243 1530 #/hr

Column 3 Run #2 T.C. #244 1000 #/hr

Column 4 Run #2 T.C. #243 1000 #/hr

Column 5 Run #3 T.C. #244 900 #/hr

Column 6 Sum

Column 7 **Average**

1 time seconds	2 °F	3 °F	4 °F	5 °F	6 °F	7 °F
1/60	10	25	32	22	89	22
2/60	22	43	42	60	167	42
3/60	22	50	44	70	186	46.5
4/60	22	58	55	72	207	52
5/60	22	68	58	81	229	57
6/60	22	77	62	78	239	60
7/60	25	77	64	104	262	65.5
8/60	30	78	67	116	291	73
9/60	47	78	83	116	324	81
10/60	30	83	88	116	317	79
11/60	32	91	94	116	333	83
12/60	48	91	92	116	347	87
13/60	48	97	77	109	331	83
14/60	40	97	80	110	327	82
15/60	42	97	80	116	335	84
16/60	51	97	80	116	344	86
17/60	52	97	80	119	348	87
18/60	55	97	83	124	359	90
19/60	68	97	83	127	375	94
20/60	72	97	83	133	385	96
21/60	70	97	85	133	385	96
22/60	72	98	92	131	393	98
23/60	72	98	92	131	393	98
24/60	72	101	92	136	401	100
25/60	77	104	92	136	409	102
26/60	77	104	92	140	413	103
27/60	68	104	92	142	406	101.5
28/60	68	101	92	142	403	101
29/60	72	104	92	142	410	102.5
$\frac{1}{2}$	74	104	92	142	412	103
3/4	84	104	92	143	423	106
1	93	107	106	143	449	112
$1\frac{1}{4}$	95	116	106	143	461	115
1-1/2	116	123	110	143	492	123

1 time seconds	2 °F	3 °F	4 °F	5 °F	6 °F	7 °F
1-3/4	123	123	118	143	507	127
2	130	130	127	150	537	134
2½	134	137	128	166	565	141
3	134	137	136	166	573	143
3½	135	137	140	170	582	145
4	138	140	140	174	592	148
4½	138	140	142	175	595	149
5	144	147	142	175	608	152
5½	144	147	142	177	610	152.5
6	147	147	145	182	621	155
7	153	156	148	184	641	160
8	156	156	150	184	646	161.5
9	158	156	155	184	653	163
10	158	166	160	---	484	161

Data runs 3-6 140 psia. 353°F saturated steam

Column 1 Time seconds

Column 2 Run #4 T.C. #243 660 #/hr

Column 3 Run #4 T. C. #244 660 #/hr

Column 4 Run #5 T.C. #243 600 #/hr

Column 5 Run #6 T.C. #244 750 #/hr

Column 6 Sum

Column 7 Average

1 Time Seconds	2 °F	3 °F	4 °F	5 °F	6 °F	7 °F
1/60	7	19	13	9	48	12
2/60	9	22	33	9	73	18
3/60	31	26	38	13	108	27
4/60	47	49	42	19	157	39
5/60	47	62	47	21	177	44
6/60	49	63	57	25	194	48.5
7/60	68	80	69	42	259	65
8/60	68	87	72	62	289	72
9/60	75	78	87	74	314	78.5
10/60	95	72	98	76	341	85
11/60	97	77	106	74	354	88.5
12/60	84	92	106	76	358	89.5
13/60	84	101	108	69	362	90.5
14/60	83	101	111	76	371	93
15/60	81	97	115	78	371	93
16/60	87	99	115	82	383	96
17/60	101	106	117	90	414	103.5
18/60	101	121	117	92	431	108
19/60	101	129	117	92	439	110
20/60	101	133	118	91	443	111
21/60	98	133	122	83	436	109
22/60	93	129	122	80	424	106
23/60	90	125	122	84	421	105
24/60	90	125	122	84	421	105
25/60	93	125	122	89	429	107
26/60	93	125	122	89	429	107
27/60	97	129	122	92	440	110
28/60	97	129	126	93	445	111
29/60	98	130	124	99	451	113

1 Time Seconds	2 °F	3 °F	4 °F	5 °F	6 °F	7 °F
1/2	101	133	126	95	455	116
3/4	101	136	126	--	363	121
1	101	136	126	--	363	121
1-¼	104	136	130	--	370	123
1-½	101	136	128	--	365	122
1-3/4	101	137	126	--	364	121
2	101	139	126	--	366	122
2-½	103	151	135	--	389	130
3	115	160	137	--	412	137
3-½	111	174	137	--	422	141
4	119	176	137	--	432	144
4-½	122	176	137	--	435	145
5	132	177	139	--	448	139
5-½	125	177	139	--	441	147
6	126	177	139	--	442	147
7	133	182	139	--	454	151
8	133	185	139	--	457	152

Data Average 8 runs

Column 1 Time seconds

Column 2 90 psia

Column 3 140 psia

Column 4 Sum

Column 5 Average

1 Time Seconds	2 °F	3 °F	4 °F	5 °F
1/60	12	22	34	17
2/60	18	42	60	30
3/60	27	46.5	73.5	36.75
4/60	39	52	91	45.5
5/60	44	57	101	50.5
6/60	48.5	60	108.5	54.25
7/60	65	65.5	130.5	65.25
8/60	72	73	145	72.5
9/60	78.5	81	159.5	79.75
10/60	85	79	164	82
11/60	88.5	83	171.5	85.75
12/60	89.5	87	176.5	88.25
13/60	90.5	83	173.5	86.75
14/60	93	82	175	87.5
15/60	93	84	177	88.5
16/60	96	86	182	91
17/60	103.5	87	190.5	95.25
18/60	108	90	198	99
19/60	110	94	204	102
20/60	111	96	207	103.5
21/60	109	96	205	102.5
22/60	106	98	204	102
23/60	105	98	203	101.5
24/60	105	100	205	102.5
25/60	107	102	209	104.5
26/60	107	103	210	105
27/60	110	101.5	211.5	105.75
28/60	111	101	212	106
29/60	113	102.5	215.5	107.75

1 Time Seconds	2 °F	3 °F	4 °F	5 °F
½	116	103	219	109.5
3/4	121	106	227	113.5
1	121	112	233	116.5
1-¼	123	115	238	119
1-½	122	123	245	122.5
1-3/4	121	127	248	124
2	122	134	256	128
2-½	130	141	271	125.5
3	137	143	280	140
3-½	141	145	286	143
4	144	148	292	146
4-½	145	149	294	147
5	139	152	291	145.5
5-½	147	152.5	299.5	149.75
6	147	155	202	151
7	151	160	311	155.5
8	152	161.5	313.5	156.75
9	---	163	---	163
10	---	161	---	161

Data T.C.#4

Column 1 Time Seconds

Column 2 Run #3 90 psia 900 #/hr

Column 3 Run #5 140 psia 600 #/hr

Column 4 Sum

Column 5 Average

1 Time Seconds	2 °F	3 °F	4 °F	5 °F
.75	0	7	7	3.5
1	7	13	20	10
1.2	9	18	27	13.5
1.5	15	23	38	19
1.75	22	29	51	25.5
2	22	33	55	27.5
2.5	36	40	76	36
3	44	46	90	45
3.5	55	54	109	54.5
4	65	62	127	62.5
4.5	72	67	139	69.5
5	75	72	147	73.5
5.5	82	74	156	78
6	86	77	163	81.5
7	95	86	181	90.5
8	100	95	195	97.5
8.5	106	95	201	100.5

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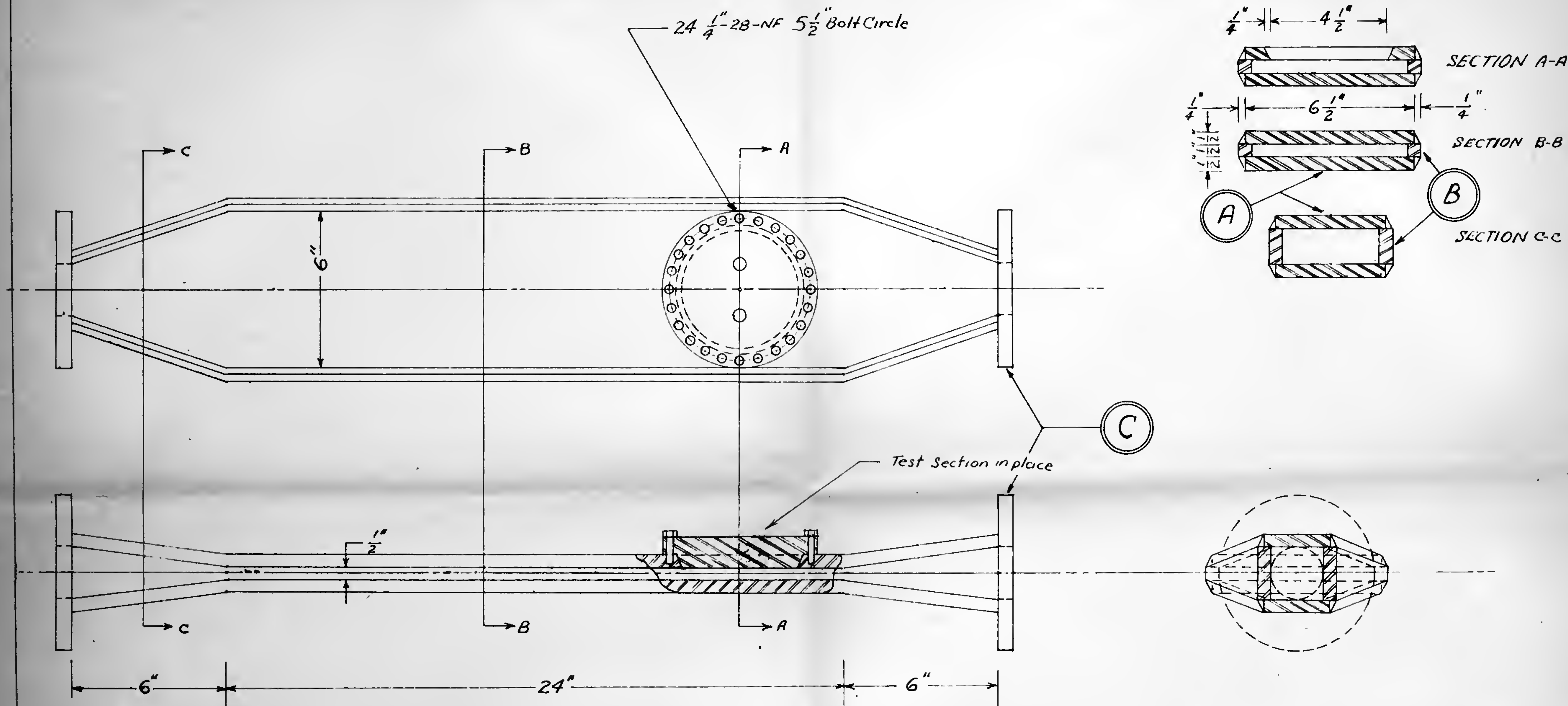


See Detail Drawing For Dimensions and Tolerances

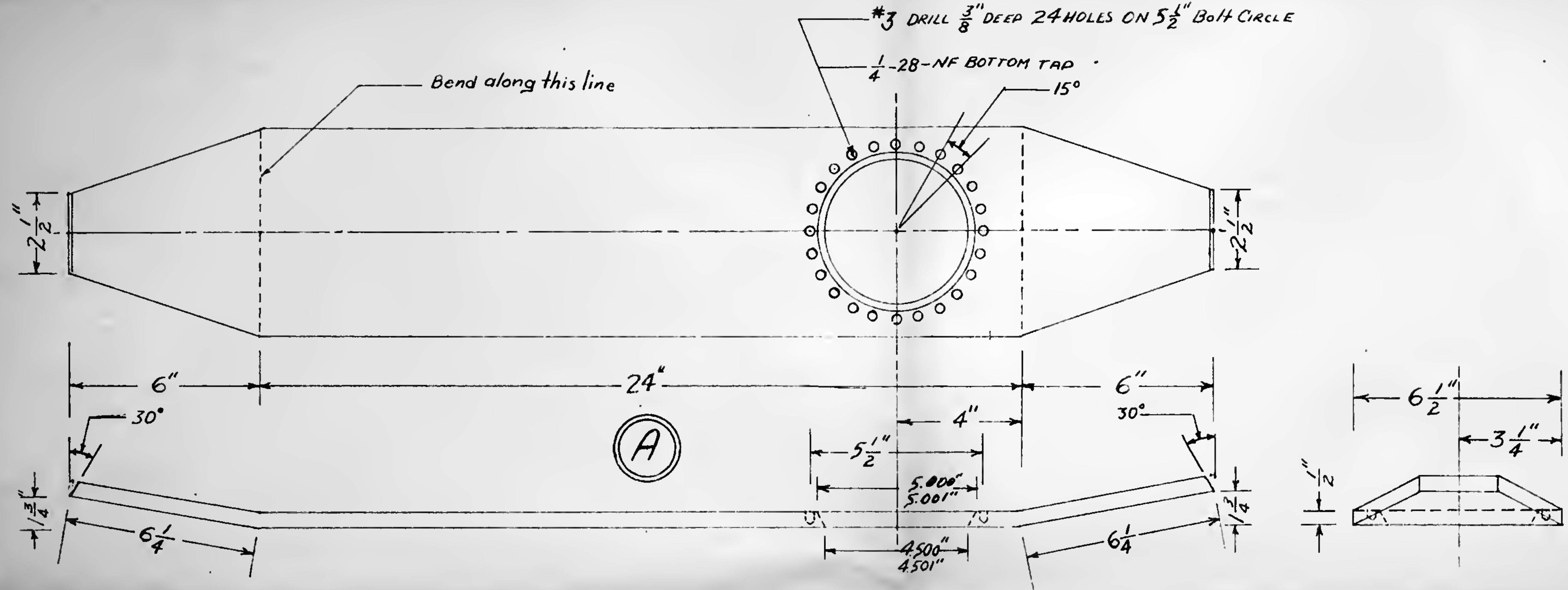
To be constructed of 1/2" mild steel plate - assembled by welding seams

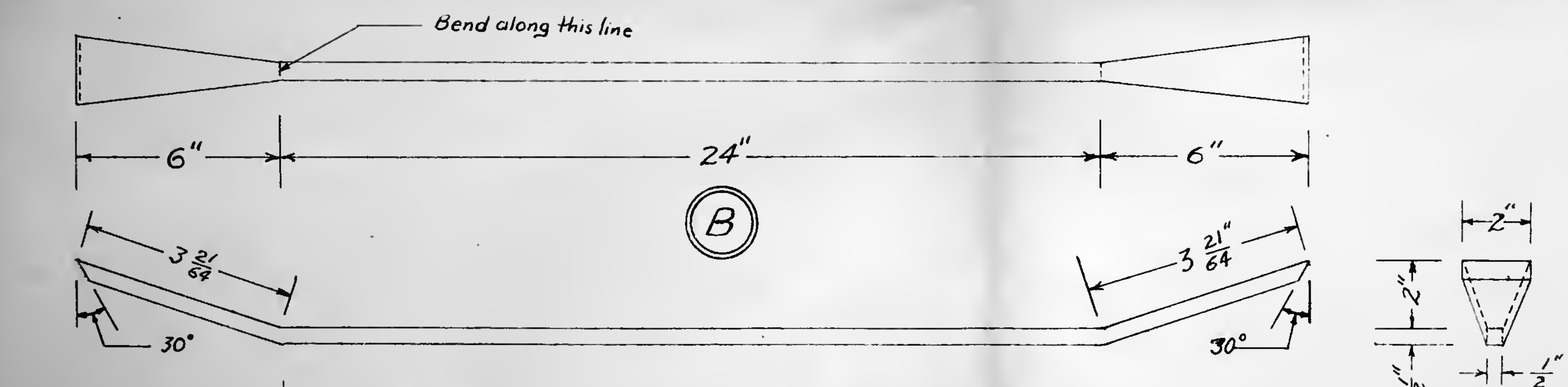
TEST SECTION CARRIER ASSEMBLY

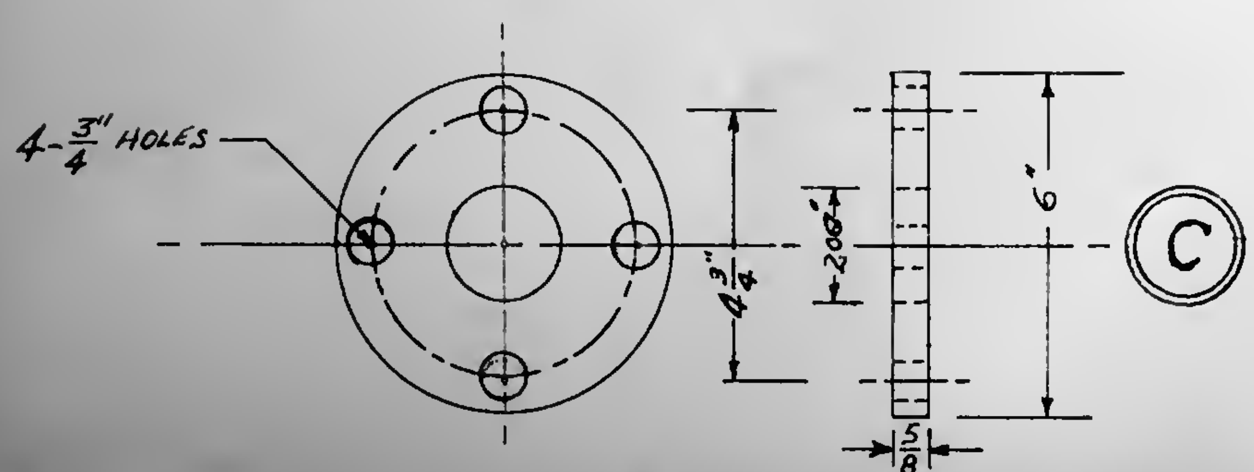
SCALE 3"=1 ft.

C.E. Arnold

FIG. 3a





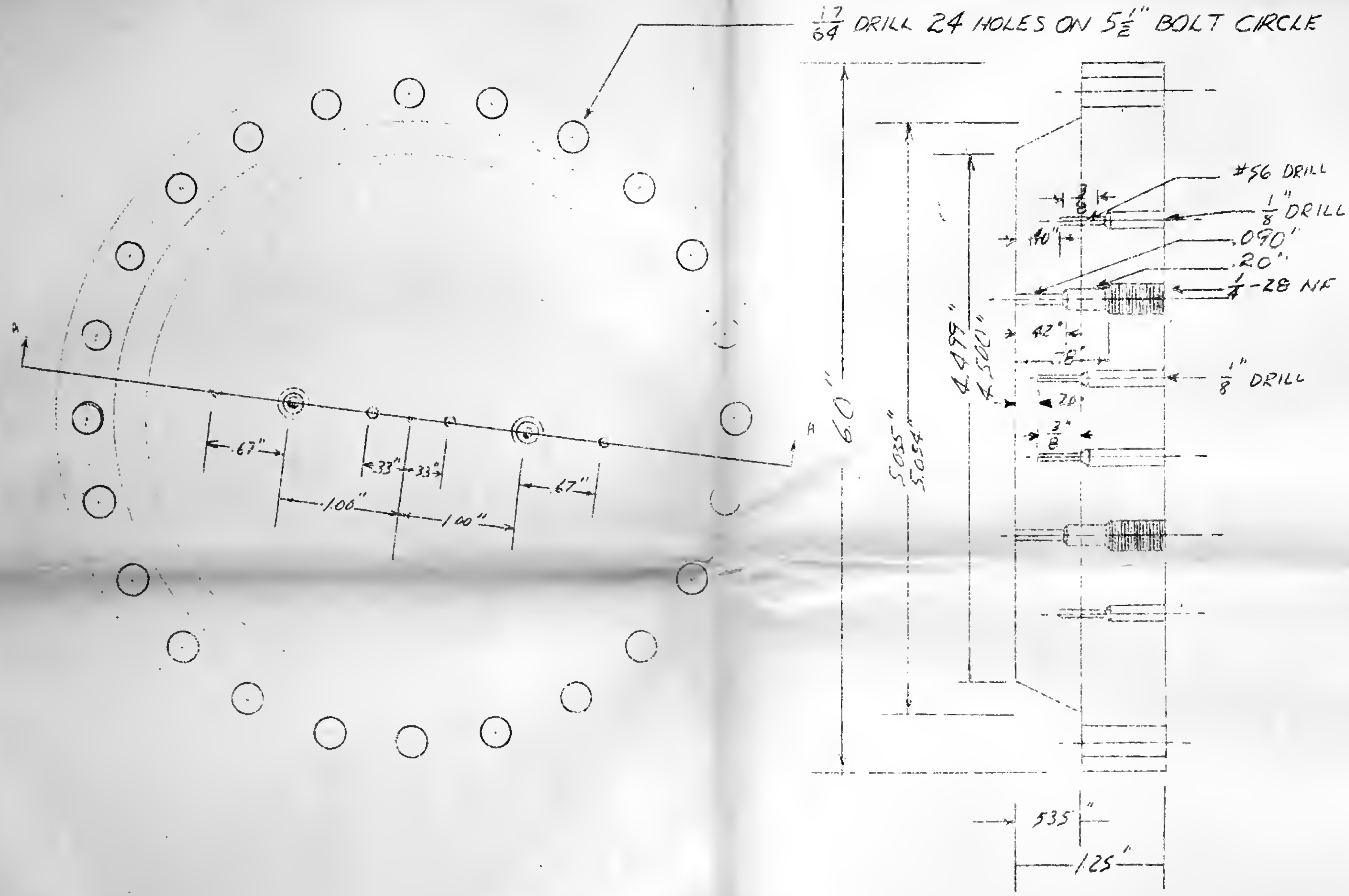


PART	NUMBER REQUIRED	MATERIAL	REMARKS
A	2	1/2" Steel Plate	Holes to be drilled in one plate after Assembly
B	2	1/2" steel Plate	
C	2	5/8" Steel Plate	

TEST SECTION CARRIER
DETAIL
SCALE 3" = 1 ft

C. E. Arnold

FIG. 3b



TEST SECTION DETAIL SCALE: FULL SIZE MAT'L SAE 4130

FIG. 3c

Arnold

Surface temperatures due to transient heat flow.

25274

Thesis
A725

Arnold

Surface temperatures due to transient heat flow.